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Title: **FIBRECAST - Fibre Reinforcement of Precision Cast Parts**

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0* ABSTRACT

The use of CFRMs (Continuous Fibre Reinforced Metals) is currently restricted particularly due to inadequate fibre and processing costs. The application of filament winding techniques combined with liquid infiltration opens up new possibilities to surmount these limits. With regard to the costs a selective reinforcement of component areas is aimed at and thus, composites with high strength in both, fibre reinforced and non-reinforced areas need to be developed. The paper reports on the development of ceramic fibre/aluminium alloy combinations suitable for producing selectively reinforced components. Specimens with a

5(M6 'Altex' fibre reinforcement have been produced by a new manufacture route based on a precision casting process. A wide range of mechanical properties has been measured including tensile strength in both directions, longitudinal and transverse to the fibre orientation. With appropriate matrices mean UTS values of about 740 MPa in longitudinal and 220 MPa in transverse direction have been produced. First results on off-fibre axis tensile tests are reported as well as on fatigue and creep tests. Al-Cu and Al-Zn-Mg alloys are suggested as highly appropriate to match the intended spectrum of properties. Two examples of potential applications with a selective fibre reinforcement are given.

1. INTRODUCTION

Merely some decades ago steel was almost the only material used for structural applications. Today design engineers have the choice of a broad spectrum of metals, ceramics and polymers with considerably varying properties. The selection is influenced particularly by technical performance, costs and, recently becoming more and more important, reusability of materials and products, respectively. New developments are driven by the objective to design materials with a spectrum of properties tailored specifically to the service requirements.

With respect to their technical performance, the group of metal matrix composites (MMCs) has the potential to find a broad spectrum of applications. Owing to their high performance to weight ratio, there is high interest particular y in light alloys with embedded continuous ceramic fibres w-hich offer extremely high strength and stiffness, see Table 1. Current restrictions on the application are attributable chiefly to inadequate cost-effectiveness of available processing technologies and high fibre costs.

Although a reduction of current fibre prices (>500ECU/kg) is expected when fibre production will be transfered from lab- to industry-scale facilities [1], fibre costs are still high when compared to conventional alloys. Therefore, an important reduction of materials cost seems to be feasible only by using a smaller amount of fibres. Real components usually show an uneven stress distribution. Less loaded areas need not necessarily to be strengthened. Thus, a selective reinforcement becomes important for composite applications.

Necessary requirements for selectively fibre reinforced components are sufficiently high strength and stiffness of the matrices used. Pure aluminium yields very high strength when unidirectionally reinforced with continuous fibres and has, therefore, been mainly used in CFRM (Continuous Fibre Reinforced Metals) research [2, 3, 4]. Due to low strength in non-reinforced regions and in directions transverse to the fibres, however, it is not appropriate as matrix for composites with a selective fibre reinforcement. Alloyed aluminium matrices, which exhibit at least moderate tensile strength, need to be employed.

The paper reports on results of an European Brite/EuRam research project on the development of cost-efficient CFRM-based components for structural use. Subsequent to the development of an appropriate process technology, research was focused on the optimisation of the composite material and the realisation of small representative components. With respect to a selective reinforcement, the work aimed at a certain level of mechanical properties as reinforced composite material both, longitudinal and transverse to the fibres, and as non-reinforced alloy, see **Figure 1.**

Table 1: Main properties of both, conventionally used high strength aluminium and titanium cast alloys [5], as well as the continuous fibre type Altex of Sumitomo Chemical [4] and the theoretically predicted properties of an Al-'Altex' fibre composite.

	Al-alloy A357-T61	Ti alloy Ti-6-4	*Fibre Altex SN*	Al-Fibre Composite
Chem. Composition [wt%]	Al-7%Si-0.6%Mg	Ti-6%Al-4%V	*85% γ-Al_2O_3, 15% SiO_2*	Al alloy + 50vol% Altex
Materials feature	isotropic	isotropic	*fibrous*	orthotropic
Specific Weight [gcm^{-3}]	**2.7**	4.4	3.3	3.1
Tensile Strength [MPa]	310	880	*1,800*	**1,050**
Specific Strength [km]	12	20	*55*	34
Youngfs Modulus [GPa]	72	110	*210*	141
Specific Modulus [10^6m]	2.7	2.5	6.3	4.5
CTE [$10^{-6} \cdot K^{-1}$]	22	12	*≈ 4*	≈ 8

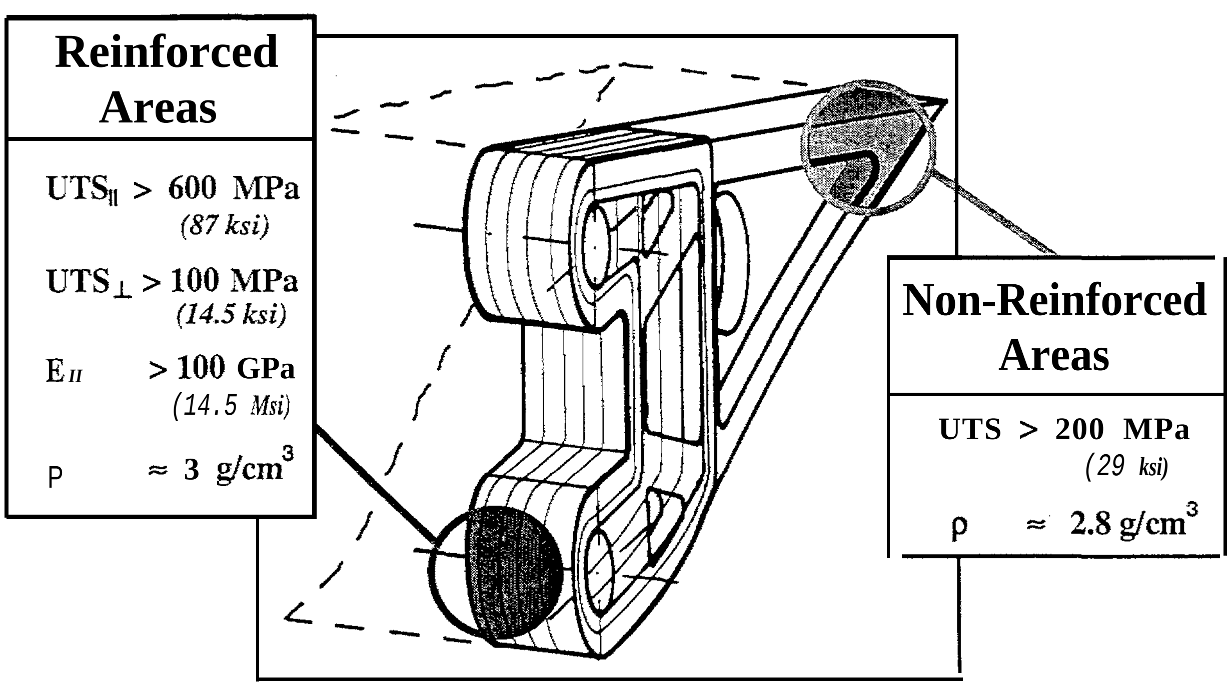

Fig. 1: Minimum requirements of the mechanical properties of continuous fibre composites for use in selectively fibre reinforced components, here shown by the example of an aileron rib fitting of an airplane [6].

2. TECHNICAL DESCRIPTION

2.1 PROCESS DESIGN

A new precision casting route has been developed for processing of selectively fibre reinforced aluminium components. The production technique is based on investment casting which is well established for manufacture of high-quality components primarily for the aerospace sector. Main benefits of the investment casting process are high design freedom, near-net-shape production and cost-efficiency for small to medium series numbers. In comparison to the conventional technique, certain modifications have been made in the pattern manufacture and casting substeps, see flow chart in **Figure 2.** High design flexibility is ensured by employing filament winding techniques known from fibre reinforced polymers. Infiltration of the molten aluminium into the fibres is supported by inert gas pressurisation. With respect to real applications, the modified investment casting process seems to be suitable for an economic and flexible production strategy.

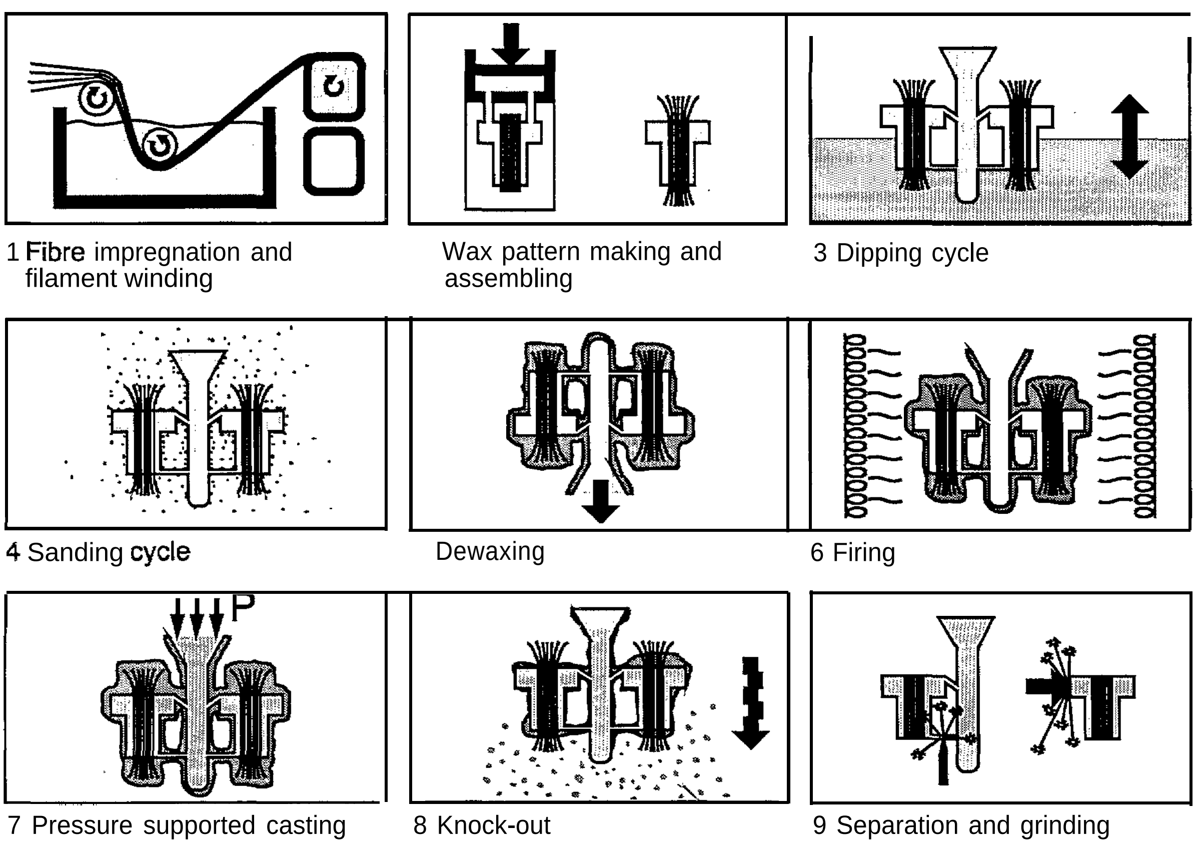

Fig. 2: Flow diagram of the modified investment casting process for production of aluminium-fibre composites. The wax pattern fabrication substep can be combined with flexible filament winding techniques [7].

2.2 MATERIALS SELECTION

It is well known from fundamental composite studies that the choice of the composite constituents has a strong impact on mechanical properties. A good chemical compatibility between embedded fibres and surrounding metallic matrix is one main requirement to produce a clean interface and thus, to achieve high composite strength. Alumina-based fibres are highly suitable as reinforcements in aluminium based alloys [8, 9].

Owing to its good handability in composite manufacture the alumina-silica fibre 'Altex' of Sumitomo Chemical/Japan has been chosen for most of the experiments, see **Table 1.** This fibre type has a filament diameter of 15pm and offers mean values of 1,800 MPa in tensile strength and 210 GPa in the elastic modulus. For comparison a smaller amount of specimens were reinforced with the pure alumina fibre 'Nextel 610' of 3M Company/USA. The Nextel fibre shows nearly the same level of tensile strength (about 2,000 MPa), but a considerably higher elastic modulus of approximately 420 GPa. All specimens have been produced with a fibre volume fraction of about 50%.

Besides chemical compatibility the formation of microstructure of the matrix is regarded as a second important aspect for composite properties [1 O, 11]. With respect to the dominating hardening mechanism two types of alloys can be distinguished: precipitation hardenable and solid solution hardenable alloys. Owing to the highly efficient hardening effect almost all technical Al alloys used for structural or engine applications belong to the group of precipitation hardenable alloys, such as Al-Cu (2000 series), Al-Si (4000 series), Al-Mg (5000 series), Al-Mg-Si alloys (6000 series), Al-Zn-Mg-Cu (7000 series) and Al-Li (8000 series) alloys. Castings of these alloys in the -T6 heat treated condition reach an ultimate tensile strength of up to 420 MPa [12].

In contrast, solid solution hardenable alloys are composed of element whose concentrations do not exceed their equilibrium solid volubility and thus, show a microstructure nearly free of second phase precipitations. Solid solution hardenable alloys therefore usually contain low element concentrations (e.g. alloys of the 1000 series). The hardening effect of solid solutions, however, is lower as compared to precipitations. Maximum tensile strength reaches up to about 250 MPa [12].

Phase precipitations have been identified to play a decisive role in the mechanical behaviour also of continuous fibre reinforced Al. In contrast to their effect in monolithic alloys, however, precipitations in CFRMs can significantly decrease strength. As examples, comparably low composite strength was reported on SiC fibre reinforced Al-Si-Mg [3], Al_2O_3 fibre reinforced Al-Cu [13] and Al-Li alloys [14].

The work reported in this paper has systematically investigated aluminium alloy systems concerning their potential to meet the minimum property goals described above. In a first step binary alloy matrices of types Al-Cu, Al-Mg, Al-Si and Al-Zn were investigated with element concentrations ranging between O and 10 wt.%. In a second step the most appropriate alloy candidates were identified and optimised.

3. COMPOSITE PROPERTIES

3.1 LONGITUDINAL TENSILE STRENGTH

Tensile tests in longitudinal fibre direction were carried out with round test specimens with 4 mm in diameter and 15 mm in parallel length. A minimum of 4 tests were carried out for each alloy type, and with most of them more than 10 tests have been performed.

Figure 3 shows the development of the ultimate tensile strength of aluminum-fibre composites in dependence on the alloy element concentration. With *pure Al* as reference matrix a high composite strength of 732 MPa was measured which is slightly lower than comparable literature values obtained by squeeze casting [4]. The additions of alloy elements show considerable differences in their influence on strength.

The Al-Zn system solely shows a high UTS over the entire range of up to 10 wt%. The average values vary between 655 and 842 MPa with the highest strength achieved with the Al-8%Zn alloy. The other systems show a higher strength compared to the pure Al matrix in low to medium element additions, but a more or less significant decrease at higher concentrations. With Al-Cu, very good strength of about 750 to 920 MPa has been measured with additions of up to 2 wt%. At higher concentrations, strength decreases in a near linear curve. The Al-Mg and Al-Si systems show an earlier and more significant drop. Only in element concentrations of less than 1 wt% these systems exceed the reference UTS of 732 MPa. With **2°/0,** however, strength falls down to about 500 MPa and decreases further when alloying more of the elements.

Microstructural investigations were employed for analysis of the composites. In case of Al-Cu and Al-Si matrices the presence of precipitates were determined to be responsible for the decrease of strength. At higher element concentrations both the amount and size of second phase crystals increases considerably, and they preferably agglomerate on fibre surfaces or in close neighbourhood to them. Due to local stress concentrations during loading the precipitates are identified as main causes for low or only moderate strength. In case of Al-Mg alloys interracial reaction products have been found at higher concentrations of Mg. Reactions took place obviously between the silica of the fibres and magnesium of the alloy resulting in the formation of a layer of fine MgO crystallite and the $MgAl_2O_4$ spinell.

Based on the results of the binary alloy matrix types the further development has lead to ternary alloys of the type Al-Zn-Mg. A number of alloys of this type are known to exhibit highest strength of conventional aluminium based alloys (7000 serie). Best results concerning processing of fibre composites have been achieved with Zn concentrations in the range of 4 to 10 wt% and Mg concentrations of about 1 wt%. Reinforced with the two continuous fibre types maximum tensile strengths of 1130 MPa (Altex fibres) and 1250 MPa (Nextel fibres), respectively, have been measured. **Figure 4** shows the comparison of weight specific strength of Al alloy - fibre composites and metal alloys conventionally used for structural applications. In relation to aluminium and magnesium alloys an increase of up to the triple value are given, and even in relation to the high-strength titanium alloy Ti-6-4 the specific strength is approximately 30°/0 higher.

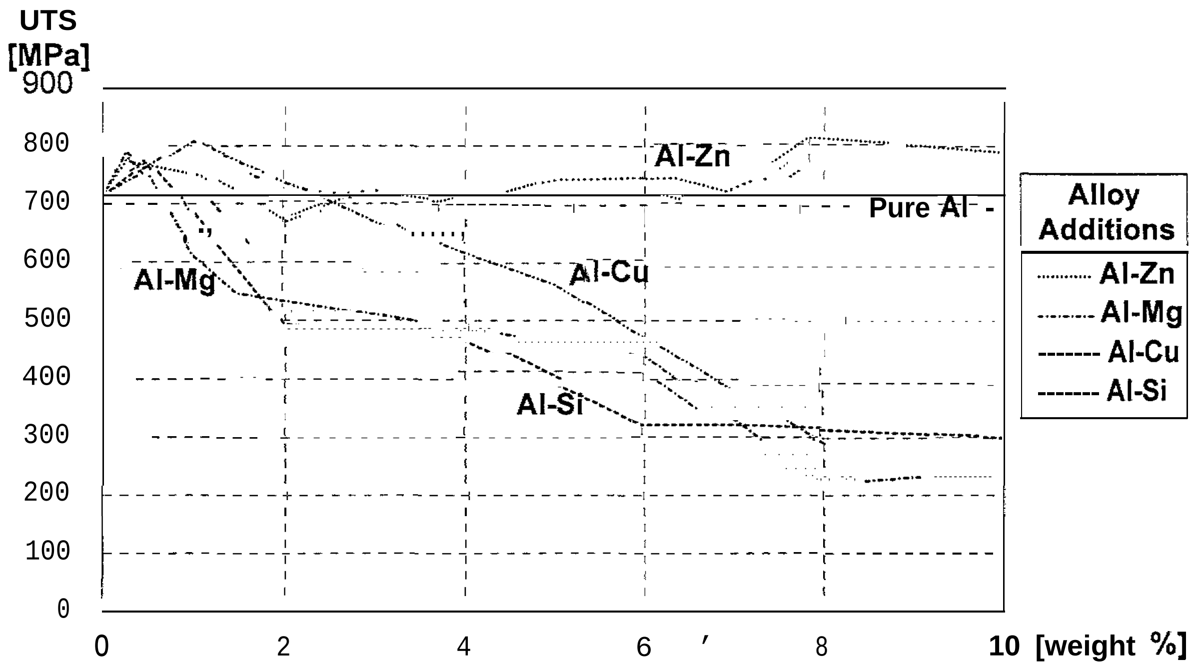

Fig. 3: Ultimate tensile strength of Altex fibre reinforced aluminum alloys of the binary systems Al-Cu, Al-Mg, Al-Si and Al-Zn in dependence on the alloy element concentration. The UTS value of the composite with a pure aluminum matrix is given as reference.

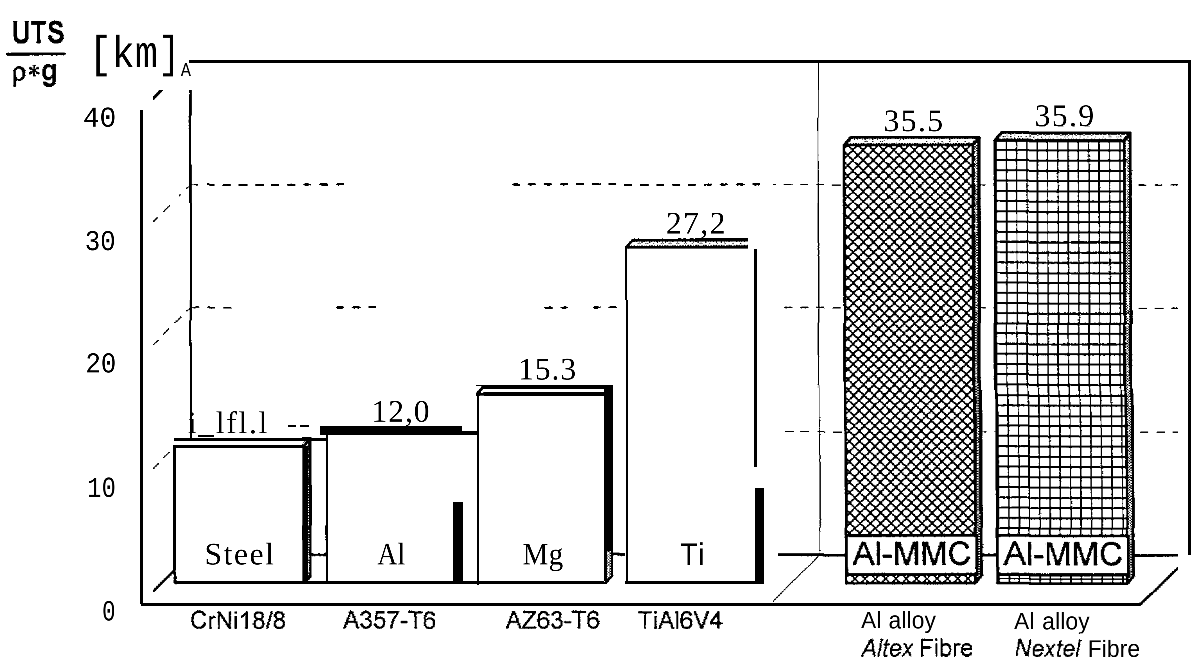

Fig. 4: Weight specific tensile strength of conventional structural metals in comparison to continuous fibre - aluminum matrix composites. High strength of the composites combined with low specific weight results in specific strength values even 30°/0 higher as compared to titanium alloys.

3.2 OFF-AXIS TENSILE STRENGTH

Transverse (90°) strength has been measured with flat specimens with a cross section of 2 x 7 mm^2. The specimens were separated from larger plates. Both, tensile and 4-point bending tests were performed with a specimen measurement length of 10 mm. Specimens have been produced with Altex fibres and a number of different matrix alloys of the system Al-Zn-Mg including pure Al and Al-1 %Mg. A minimum of 3 tests were performed with each alloy type. Test results are given in **Figure** 5. Bending tests obviously produce considerably higher strength values than tensile tests. In some cases flexural strengths exceed the tensile strength by more than 100%. With pure aluminium matrix a transverse flexural strength of about 160 MPa was measured, Alloy additions of zinc and magnesium could increase strength to values of about 340 MPa.

Off-axis tensile strength was measured in a range of 0° and 45° between fibre orientation and load direction. Tensile tests have been carried out with flat specimens mechanically cut from larger plates. **Figure 6** shows tensile test results plotted versus the. off-axis angle in the range between O and 21°. Strength decreases nearly linear from about 600 MPa to 380 MPa. However, the measurement value for the 0° orientation (longitudinal diection) is notably lower as compared to the tensile strength result measured with round specimens. The diffrence might be caused by a higher rate of non-infiltration defects in the large plates used for producing specimens for off-axis measurements.

3.3 YOUNG'S MODULUS AND STRAIN-TO-FAILURE

The elastic moduli of materials have been calculated from the stress-strain curves taking the three stages into account that are typically measured with CFRM composites. In the first stage both constituents, fibres and aluminium, deform elastically. At the flow strength of the matrix, plastic deformation starts while the fibres' deformation remains elastic. In the third stage both materials deform plastically [15]. In the experiments, mainly the first two stages could be detected. Only with a few specimens a third stage was observed. The values of both stages show a remarkable dependence on the matrix alloy, and a strong relation to the fibre type used. For the first stage values ranged between 100 and 155 MPa for Altex fibre composites, and between 200 and 280 MPa for Nextel fibre composites. In the second stage the values ranged between 85 and 120 MPa (Altex) and between 150 and 230 MPa (Nextel). The strong influence of the fibre type is caused by the big difference in the elastic modulus of the fibres materials (210/420 GPa). In **Figure 7 the** weight specific elastic modulus of conventionally used structural metals and the fibre composites are compared. While the monolithic metal alloys are within a small range between 2.47 and 2.74, the metal matrix composites show much higher values. With Altex fibres an increase of about 50°/0 was measured. With Nextel fibres the material reaches almost the triple value of specific strength.

Strain-to-failure values, however, showed a more significant influence of the matrix used. Plastically high deformable matrices result in highest strain of the composites. Maximum values in the range of 0.8 to 0.9 °/0 were found with pure Al, Al-Zn or Al-Cu matrices. Lowest strain-to-failure of 0.27 % was measured for composites with an Al-4%Mg matrix, probably caused by the formation of brittle interracial products.

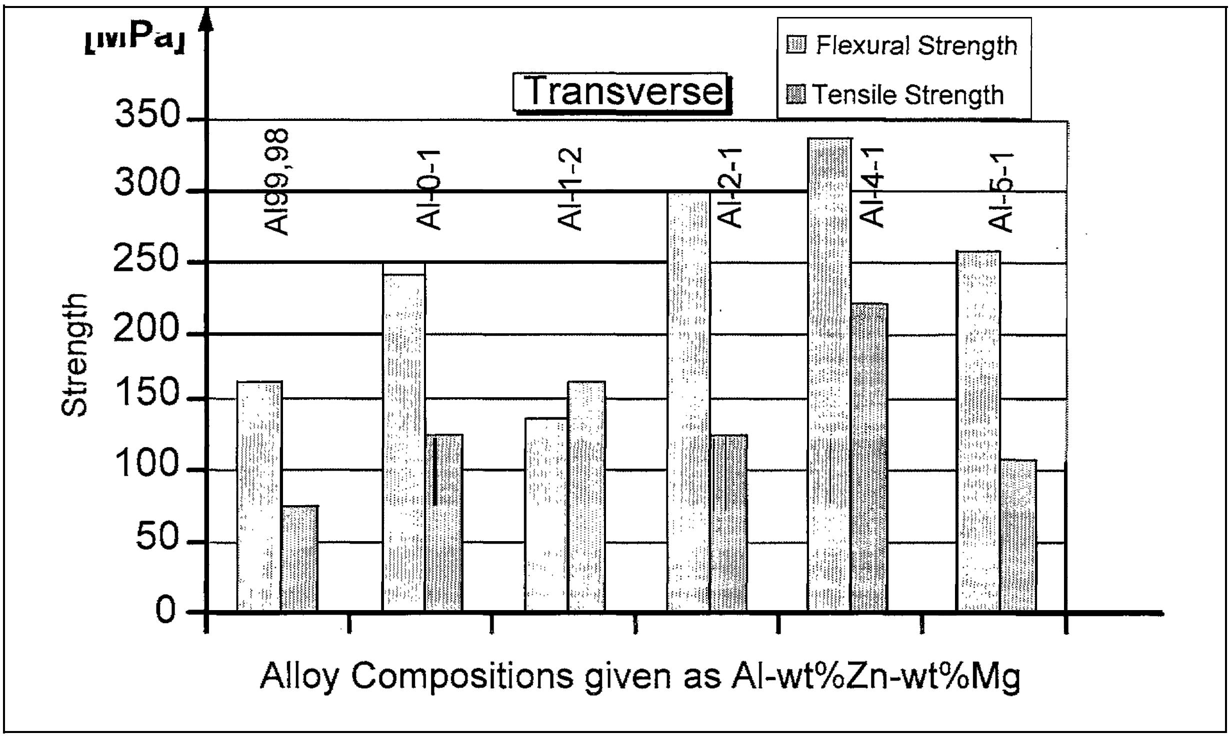

Fig. 5: Transverse (direction 90° to the fibre orientation) tensile and flexural strength of Altex fibre composites with different matrix alloys of the system Al-Zn-Mg.

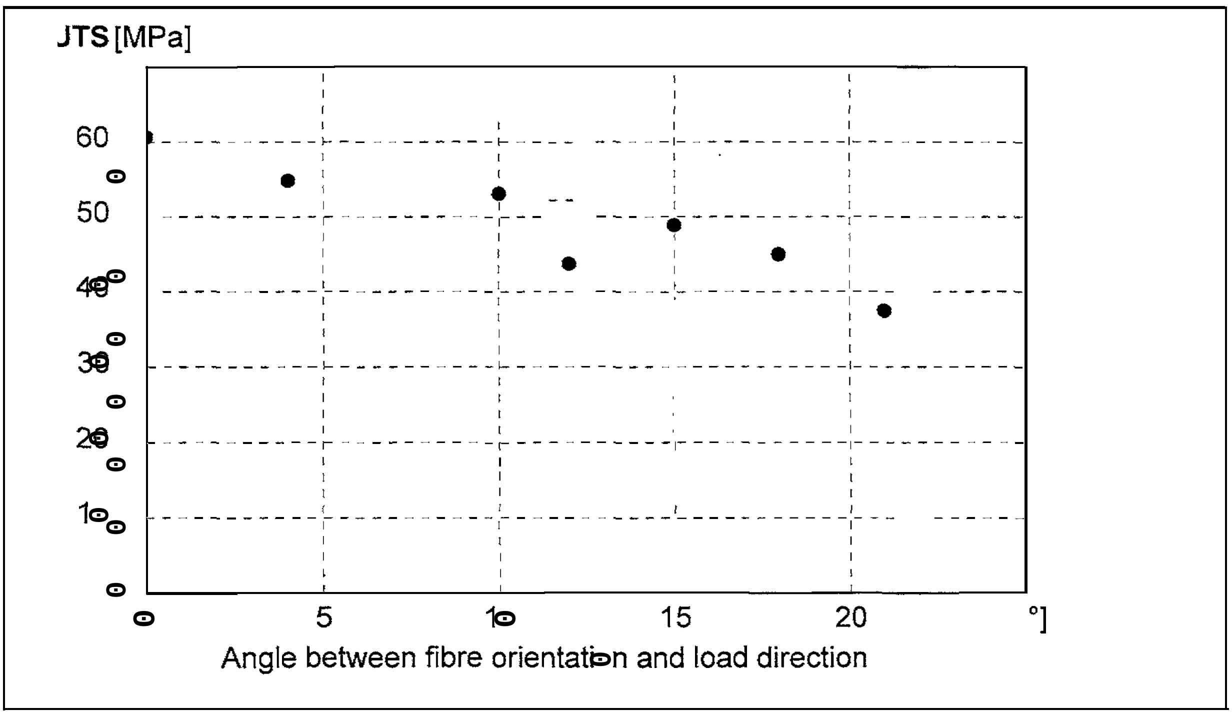

Fig. 6: Off-axis (direction 0 to 20° to the fibre orientation) tensile strength of Altex fibre composites produced with Al-5%Zn-1%Mg matrix alloys.

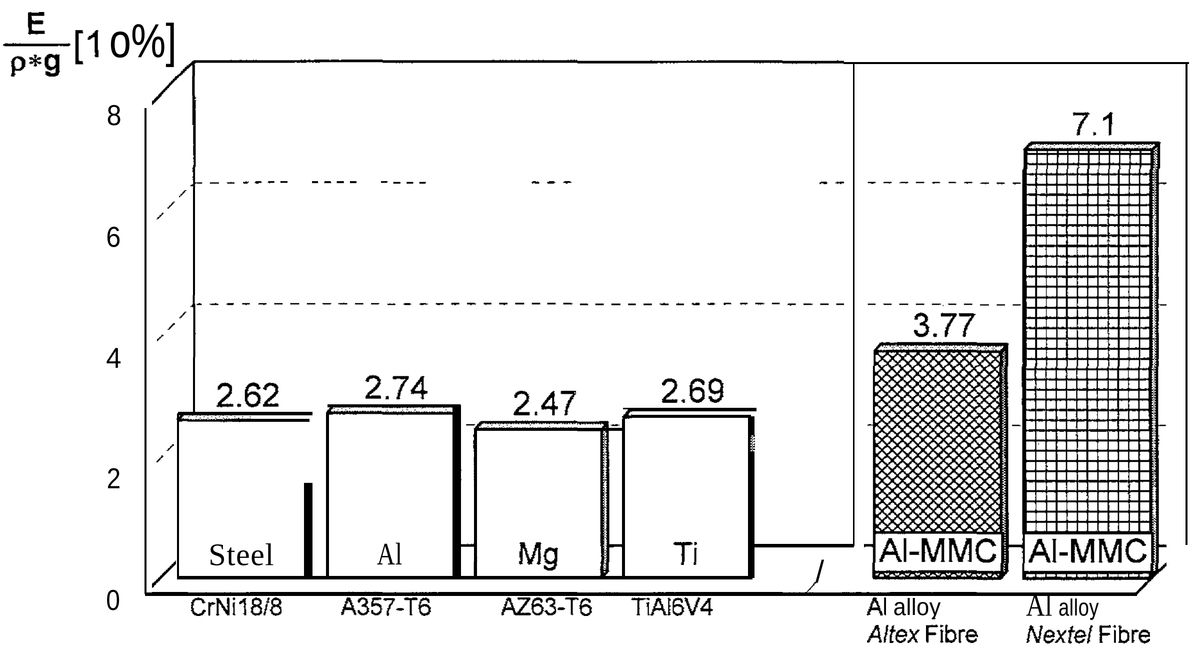

Fig. 7: Comparison of the weight specific elastic modulus of structural metals and aluminium matrix fibre composites. Owing to extraordinarily high stiffness of Nextel fibres the composites show almost triple values of the specific elastic modulus.

3.4 FATIGUE AND CREEP RESISTANCE

Fatigue testing was performed using a dynamic test machine working in full resonance. Specimens of dogbone shape with threaded grips were used. The nominal diameter of the parallel length used varied between 4 and 6.0 mm. Both, tension-tension fatigue (R-ratio of 0.1) and tension-compression fatigue (R-ratio of -1) of Altex reinforced Al-Zn-Mg alloys were measured and compared to the conventionally used aluminium-silicon casting alloy **A357-T6** 1.

Fatigue strength of the composites have been detected significantly higher compared to the monolithic alloy. In both load cases the maximum stress could be increased by 100 to 200%. **Figure 8 shows** the S,N-fatigue curve for the R-ratio of -1. Despite the great scatter in test results the comparison of the monolithic alloy with the fibre reinforced aluminium shows the high dynamic capability of the composite material.

Furthermore, first creep tests were performed at elevated temperatures of up to 180°C. Dog-bone shaped specimens were used comparable to those produced for longitudinal tensile tests. The commercially available Al-Zn-Mg alloys are known to possess low creep resistance at temperatures above 130°C. With the Altex fibre reinforcement, however, no creep has been observed in longitudinal direction, even close to the use limit of the alloy. The allowable stress level could be increased by about 200%0 as compared to conventional monolithic alloys.

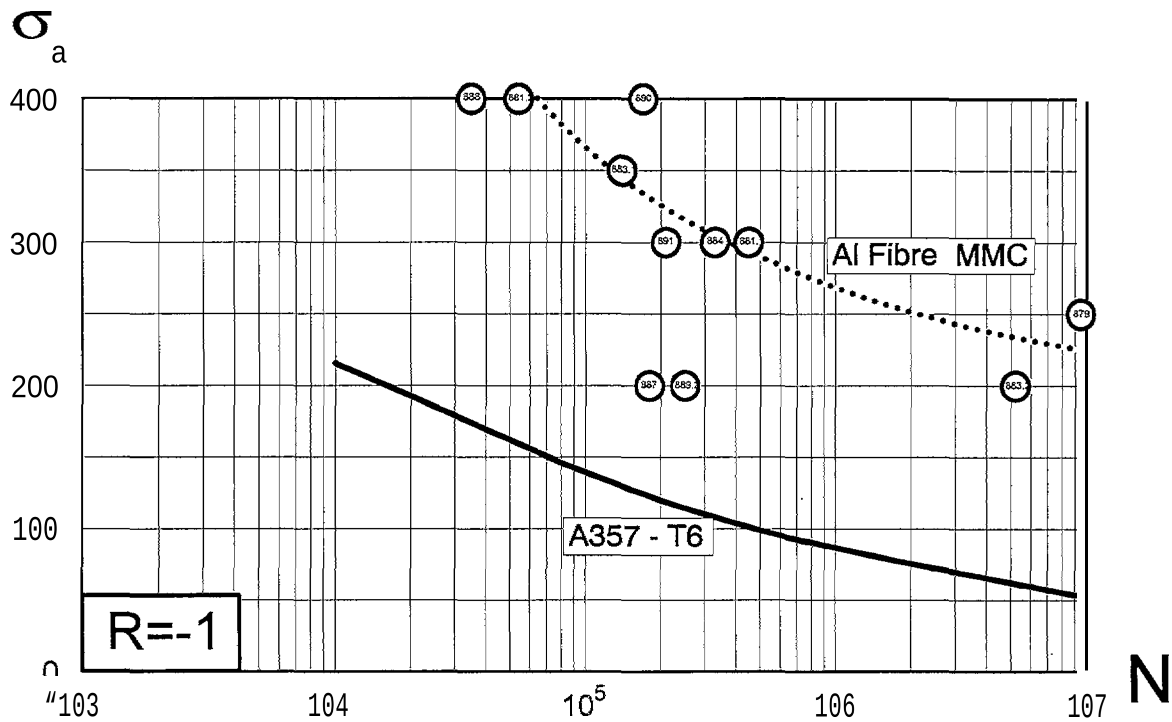

Fig. 8: S,N-fatigue curve for tension-compression loading (R-ratio of -1) of aluminium matrix composites compared to the conventionally used Al-Si alloy A357. The composites were produced with 50 vol% Altex fibres and an Al-5%Zn-1%Mg matrix alloy.

4. Conclusions

The results described show the possibility to design CFRM composites with a combination of good to excellent properties including elastic modulus, tensile and flexural strength, fatigue and creep resistance. The new process employed has shown its capability to produce fibre composites with a high efficiency in relation to theoretical values. The choice of the matrix alloy, however, has a strong influence on properties. Conventional casting alloys like AA357 (Al-7%Si-based) or AA203 (Al-4%Cu-based) are not appropriate for achieving high composite strength in longitudinal direction. The development of new aluminium alloys for use as matrices is necessary. Promising candidates are solid solution hardenable alloys such as low alloyed Al-Cu or Al-Zn-Mg matrices. The favorable character of these composite materials opens up new possibilities in the selective fibre reinforcement of aluminium castings. With strength values of more than 200 MPa transverse to the fibres and in non-reinforced areas, these types of MMCS could match requirements of structural applications that are not possible with fibre reinforced polymers [16] or carbon fibre reinforced metals [17].

Owing to its high design flexibility the newly developed precision casting route opens up new possibilities for the use of light weight metal matrix composites. Aluminium alloys with a continuous fibre reinforcement seem to be highly appropriate for structural and engineering applications with high requirements on load transfer and stiffness in both, static and dynamic loading conditions. Groups of potential end-users are the aeronautics, sports and leisure, mechanical engineering, and automotive industry. Two examples to demonstrate possibilities of an use of continuous fibres in metal components is given in **Figure 9.**

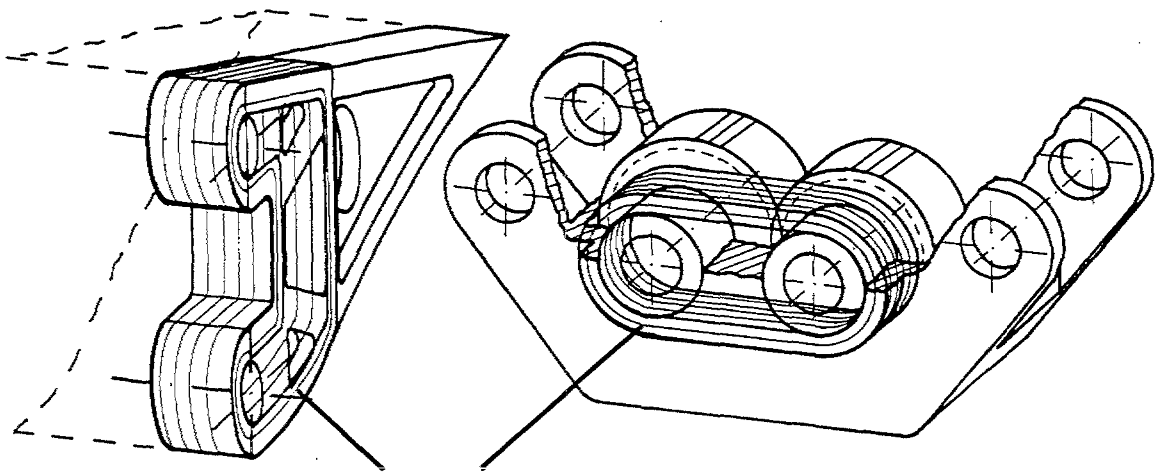

Fig. 9: Examples of potential airplane applications of aluminium alloys with selective fibre reinforcement: Primary aileron rib fitting, reinforced for the load transfer through the component (left), and gear box, reinforced for stiffening of bearings (right) [18].

5. ACKNOWLEDGEMENTS

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